Suitability of Cotton as an Alternative Crop in the Ogallala Aquifer Region

Prasanna H. Gowda,* R. Louis Baumhardt, Allison M. Esparza, Thomas H. Marek, and Terry A. Howell

ABSTRACT

Renewed interest in cotton (*Gossypium hirsutum* L.) production in the Ogallala Aquifer Region can be linked to development of early maturing varieties, rising energy costs, and declining water levels in the Ogallala Aquifer. The main objectives of this study were to assess the feasibility of growing cotton and estimate the cotton yield potential and the potential reduction in Ogallala Aquifer withdrawals by producing cotton as an alternative to corn. For this purpose, the heat unit based, county-wide exceedance probability (*P*) curves for potential cotton yield were developed using a long-term air temperature dataset (1971–2000), and counties that have the potential to produce cotton every year (*P* = 0.99), 4 out of 5 yr (*P* = 0.85), and 3 out of 4 yr (*P* = 0.75) return periods were identified and mapped. Results indicate that 91 of 131 counties in the study area have the potential to produce cotton with lint yield > 500 kg ha^{-1} 3 out of 4 yr. A county-wide lint yield goal based on a 3 out of 4 yr scenario may improve the chances for better profits to producers than with lint yield that can be expected every year. However, management uncertainties on water use efficiency; fuel, fertilizer, and pest management costs; and planting and harvesting schedule may require further consideration for estimating potential profitability. Nevertheless, these results show that cotton is a suitable alternative crop for most counties in southwest Kansas and all counties in the Texas and Oklahoma Panhandles. In addition, a significant reduction in water withdrawals from the Ogallala Aquifer for irrigation is probable if producers were to convert 50% of their land under corn to cotton production.

Cotton is the most important textile fiber in the world, accounting for more than 40% of the total world fiber production. It is grown in more than 100 countries with the USA ranking second behind China (Womach, 2004). The annual revenue generated by cotton and its products in the USA accounts for about $40 billion (USD). In the USA, cotton has largely been grown below 37° N lat. in what is called the cotton belt. In recent years, cotton production has been slowly expanding to the Central High Plains of the Ogallala Aquifer Region that covers the panhandles of Texas and Oklahoma and the southwestern counties in Kansas where corn has traditionally been produced (Colaizzi et al., 2004). This renewed interest in cotton production can be associated with the development of early maturing varieties, increasing energy prices, and declining water levels in the Ogallala Aquifer (Wheeler et al., 2004).

One of the options to reduce the use of groundwater from the Ogallala Aquifer is to utilize more drought tolerant and economically viable crops. Crop water use statistics for Texas High Plains (New and Dusek, 2005) indicate that the cotton water requirement of 647 mm is less than other major crops grown in the region, such as corn (*Zea Mays* L.; 835 mm), sorghum [*Sorghum bicolor* (L.) Moench; 688 mm] and soybean [*Glycine Max* (L.) Merr.; 681 mm]. After water, temperature is the second most yield-limiting factor in cotton production in the Central and Northern High Plains of the Ogallala Aquifer Region (Reddy et al., 1992a, 1992b). Temperature determines the length of the growing season and is strongly related to cotton yield and quality (Reddy et al., 1999; Liakatas et al., 1998; Waddle, 1984).

Cotton development rates are related to air temperature during the growing season (Roussopoulos et al., 1998; Munro, 1987; McMahon and Low, 1972) and can be expressed as accumulated heat units or growing degree days. A heat unit (HU) is a measure of the amount of heat energy a plant encounters each day during the growing season, and is calculated from daily maximum and minimum air temperature values as

$$\text{HU } ^\circ\text{C} = (^\circ\text{C}_{max} + ^\circ\text{C}_{min})/2 - \text{T}_t \ ^\circ\text{C when HU} > 0.0 \quad [1]$$

This concept of heat units resulted from observations that plants do not grow below a threshold temperature (T_t). The T_t for a cotton plant is 15.6°C. Crop growth and development of cotton are directly related to accumulated heat units when other environmental factors are not limiting (Peng et al., 1989).

The phenological heat unit requirements by crop growth stage for cotton from planting to maturity in the southern Texas High Plains are presented in Table 1. Cotton requires about 1444°C heat units from planting to maturity (Waddle, 1984). However, in recent years, farmers in the Texas Panhandle have shown that economically viable cotton can be grown with approximately one-third fewer heat units (Howell et al., 2004). That is, with 1000°C heat units, a cotton plant can produce one open boll and four more bolls that are 85% matured (Wrona et al., 1996). Crop termination through defoliation at this stage of plant development results in a loss of about 1% of total expected yield but does not reduce the fiber quality (Wrona et al., 1996).

Planting and harvesting dates of cotton impact crop growth, development, and yield (Davidonis et al., 2004; Unruh and Silvertooth, 1997). Early planting can expand the growing season and helps growers to avoid inclement weather and late-season pests (Steiner and Jacobsen, 1992). Generally, cotton is planted when soil temperature reaches 15.6°C or greater. Emergence, stand, and vigor are adversely affected when soil temperatures fall below 15.6°C. If planted too early, when

P.H. Gowda, R.L. Baumhardt, and T.A. Howell, USDA-Agricultural Research Service, Conservation & Production Research Lab., P.O. Drawer 10, Bushland, TX 79012; A.M. Esparza, Spatial Sciences Lab., Texas A&M Univ., College Station, TX 77843; and T.H. Marek, Texas Agric. Exp. Stn., 6500 Amarillo Blvd W., Amarillo, TX 79106. Received 3 Oct. 2006. *Corresponding author (pgowda@cprl.ars.usda.gov).

Published in Agron. J. 99:1397–1403 (2007).
Agroclimatology
doi:10.2134/agronj2006.0275

Abbreviations: PCY, potential cotton yield; THU, total heat units.

Table 1. Phenological heat unit requirements for development of cotton by crop stage in the southern Texas High Plains.†

Stage of development	Plant age	Required heat units (base temperature = 15.6°C)
	d	
Germination-seedling establishment	5–15	44–55
Square initiation	35–50	250–306
First flower	55–70	528–556
Peak flower	75–95	506–861
First open boll	100–120	1000–1056
50% open boll	120–140	1194–1250
80% maturity	140–170	1278–1361
100% maturity	150–180	1389–1444

† Source: D.R. Krieg, personal communication, 17 Feb. 2006.

soils are cooler than 12.8°C, a cotton crop may suffer stand loss, seedling disease problems, and cold temperature stress, which reduce yield (Sansone et al., 2002). Soil temperature at planting depth is influenced by air temperature due to the proximity of the seed zone to the atmosphere (Brown et al., 2000). Numerous models have been developed to predict soil temperature by using air temperature (Paul et al., 2004; Kang et al., 2000; Gupta et al., 1984). Esparza et al. (2006) developed a set of linear regression relationships to estimate daily minimum soil temperature from daily maximum and minimum air temperature in the Ogallala Aquifer Region. Selection of maturity date for harvesting cotton depends on first day of freezing in the fall, cotton variety, fall rainfall forecast, and/or yield goal.

Due to lower water requirements, availability of early maturing varieties, fluctuating energy prices, and declining groundwater levels, it is hypothesized that cotton is a viable alternative crop to corn in the Ogallala Aquifer Region. However, there has been no study to estimate cotton yield potential to determine physical and financial feasibility of growing cotton. The main objectives of this study were to assess the feasibility of growing cotton and estimate the cotton yield potential and the potential reduction in Ogallala Aquifer withdrawals by producing cotton as an alternative to corn.

MATERIALS AND METHODS

Study Area

This study focuses on counties located below 40° N in the Ogallala Aquifer Region, including all of the Southern and Central High Plains and a part of the Northern High Plains (Fig. 1). There are 131 counties in this region, totaling 41.32 million ha. This region has a semiarid to arid environment in the south that gradient to a subhumid environment in the north (McGuire et al., 2003). Annual precipitation in the area ranges from 366 mm in the western part to about 813 mm in the east. The major irrigated crops in the study area include corn, winter wheat (*Triticum aestivum* L.), cotton, sorghum, soybean, and peanut (*Arachis hypogaea* L.). Although the Southern High Plains is known for cotton production, it was included in our study for comparison of estimated cotton yield with measured data.

Database Development

Long-term climatic data from the National Climatic Data Center were used in this study. This dataset consists of maximum and minimum air temperature data from all weather stations in the Ogallala Aquifer Region maintained by both the National Weather Service (NWS) and local cooperating agencies. Based on the period, availability, and continuity of daily observations, a set of weather stations was selected. Daily values of maximum and minimum air temperatures were taken from a single station that had the most complete data in each county. Missing values were supplemented with data from neighboring stations within the same county. For counties with no weather stations, daily values of minimum and maximum air temperature were calculated by averaging that from surrounding counties.

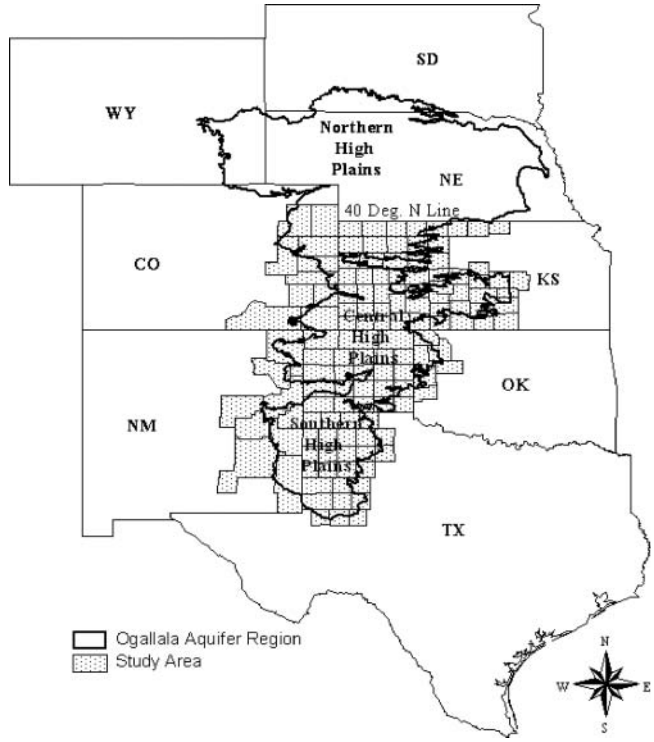


Fig. 1. Location of the study area.

Seasonal Boundary Conditions

County-wide planting date for cotton in each year was identified based on the predicted daily minimum soil temperature. Two sets of regression models reported in Esparza et al. (2006) for the Ogallala Aquifer Region were used to predict daily minimum soil temperature. One regression model was based on maximum air temperature and the other was based on minimum air temperature for each climatic division (National Climatic Data Center, 2002). Annual cotton planting dates for each county were identified when its estimated daily minimum soil temperature during the planting season was above or equal to a threshold value of 15.6°C for both statistical models. The first day of freeze or 15 October, whichever occurred first, was selected as the harvesting date. We designated 15 October as the harvest date because, in the Southern High Plains, the first frost may not occur during October; however, producers usually harvest their cotton by the second week of October to avoid late-season pests and fall precipitation events that affect fiber quality. In the Central and the Northern High Plains, frost may occur during the last week of September, effectively terminating the crop regardless of the crop maturity.

County-Wide Heat Units and Potential Cotton Yield

For each county, we calculated annual heat units available for cotton between planting and harvesting dates using Eq. [1] assuming no cotton varietal response to base temperature. Finally, the county-wide potential cotton yield (PCY, kg ha^{-1}) was calculated as:

$$\mathrm{PCY} = 0 \text{ when THU} < 800^\circ\mathrm{C} \quad [2]$$

$$\mathrm{PCY} = \left[\frac{\mathrm{THU} - 800}{41.7}\right] \times 112.5 \text{ when } 800 < \mathrm{THU} < 1000^\circ\mathrm{C} \quad [3]$$

$$\mathrm{PCY} = \left[5 + \frac{\mathrm{THU} - 1000}{41.7}\right] \times 112.5 \text{ when THU} > 1000^\circ\mathrm{C} \quad [4]$$

where THU is the total heat units accumulated (°C) during the growing season in a given year. The proposed equations are based on three assumptions: (i) PCY is equal to zero when THU is less than 800; (ii) with 1000 heat units accumulated, the cotton plant will have one open boll with four more bolls at 85% maturity level and produces approximately 560 kg ha^{-1} (500 lb ac^{-1}) of cotton lint under irrigated conditions (Wrona et al., 1996); and (iii) with every additional 41.7°C heat unit accumulation (≈75°F), cotton produces one more harvestable boll (Sansone et al, 2002). Equations [2], [3], and [4] were used to estimate PCY for counties with THU less than 800, in the range of 800 to 999, and above 999, respectively. With THU in the range of 800 to 999, cotton can be grown; however, it may not be economically viable under irrigated conditions as it results in low lint yield (Clay et al., 2006).

Climatic variability from year to year impacts cotton yield as it affects total plant available heat energy during the growing season. Better understanding of climatic variability is important for producers. It helps in setting realistic yield goals and in planning appropriate management practices. Therefore, the PCYs for each county were ranked in decreasing order and the exceedance probability (P) was calculated as:

$$P = \frac{N}{(n+1)} \quad [5]$$

where N is the rank of the annual estimated value and n is the total number of years (Davis et al., 2000; Haan et al., 1994). In this study, the n is equal to 30. The exceedance probability for an event of a given magnitude is defined as the probability that an event of equal or greater magnitude will occur in any single year. The return period is the inverse of the P. For example, an event with a P of 0.25 occurs at least once in 4 yr or a PCY with a P of 0.75 occurs in 3 out of 4 yr. Intuitively, producers want to know the lowest possible PCY that they expect in their county in any given year (1 yr return period), that is, $P = 0.99$. The next thing producers would want to know is, how much more yield they can expect if they were to take some risk, because higher yield goals involve higher input (irrigation, fuel, fertilizer, etc.) cost. Some scenarios that may be of interest to producers would be a PCY at $P = 0.85$ (4 out of 5 yr) or $P = 0.75$ (3 out of 4 yr), where producers can expect a PCY higher than the minimum.

A set of maps was generated using Arcview 3.3 (ESRI, 2002) to illustrate the spatial distribution of heat units and PCY over the study area. It included county-wide, long-term, average heat unit and potential yield maps; and PCY maps with exceedance probabilities of 0.99 (every year), 0.80 (4 out of 5 yr), and 0.75 (3 out 4 of years).

Potential Water Conservation

Finally, a county-wide preliminary estimate of the potential reduction in irrigation withdrawals was made by converting 50% of the crop land under corn to cotton in counties with PCY 560 kg ha^{-1} (or THU of 1000°C) or more lint at a P of 0.99. We assumed that both corn and cotton were grown under fully irrigated conditions and crop water demand for corn and cotton were 835 and 647 mm, respectively, throughout the study area. In reality, crop water and irrigation demands change from one region to another due to spatial variability in the climatic conditions, evapotranspiration, and precipitation pattern during the growing season (Baumhardt and Salinas-Garcia, 2006).

RESULTS AND DISCUSSION

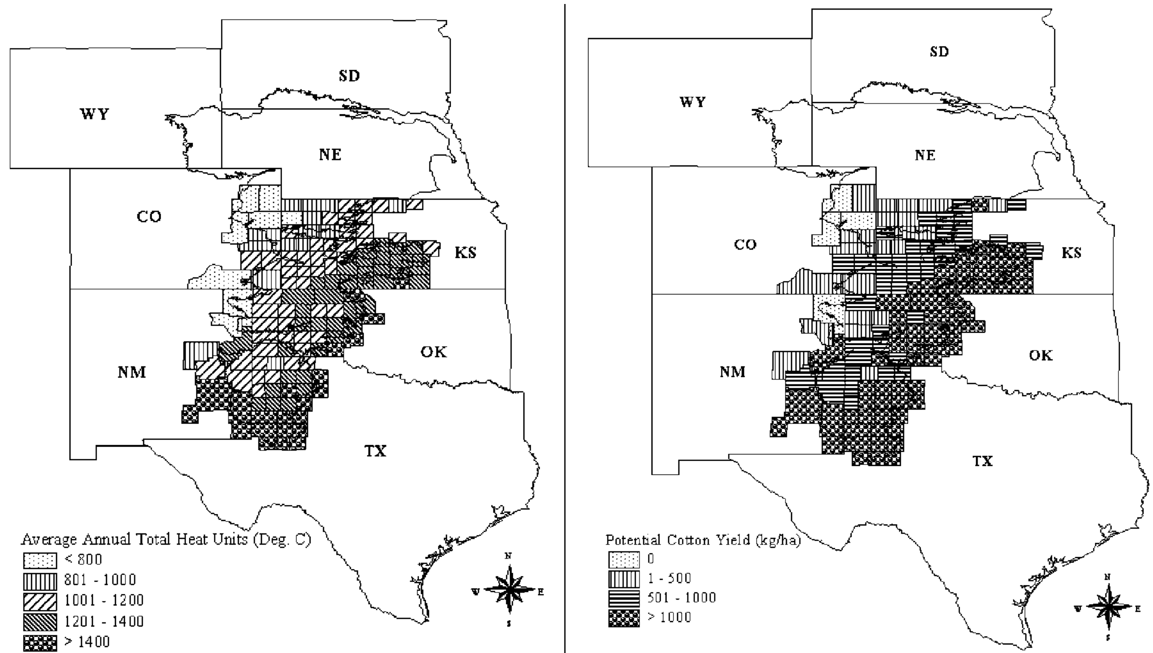
Seasonal Boundary Conditions

Using long-term (1971–2000) air temperature data, we calculated the county-wide THU during the growing season and corresponding PCY for each year. For most counties, the planting dates were between 1 and 15 May. However, counties around Lubbock, TX, in the Southern High Plains had planting dates between 15 and 30 April. Counties in the western part of the Central High Plains had late planting dates between 25 May and 15 June as their elevation and latitude are relatively higher than the Southern High Plains.

County-Wide Total Heat Units

Figures 2a and 2b show the spatial distribution of county-wide long-term average THU and PCY in the study area, respectively. For any given longitude within the study area, the THUs were higher for southern counties than northern counties. This is because the latitudes of the southern counties are relatively lower than those of northern counties and consequently they receive more solar energy. Similarly, the THUs were higher for counties in the eastern half of the study area compared with counties in the western half. This is because eastern counties are located at relatively lower elevation and therefore experience higher soil and air temperatures, which facilitate earlier planting dates. County-wide long-term average THUs varied from 582°C in Union County, NM, to 1724°C in Ector County, TX (Fig. 2a). Lower accumulation of heat units in Union County is due to its higher elevation (1816 m) and latitude (36.50° N). In contrast, Ector County is located in the southernmost part of the study area with relatively lower elevation (885 m) and latitude (31.88° N) and consequently it recorded higher heat units.

Of 131 counties in the study area, 105 counties including all of the counties in the Texas High Plains except Castro (998°C), the Oklahoma Panhandle, and southwestern Kansas recorded 1000°C or more heat units. Castro County recorded lower long-term average THUs than all other counties around it. This may be due to errors in the temperature data for that county. Only two of 10 counties in Colorado recorded more than 1000°C heat units. In this study, we used a THU of 1000°C as a cut-off point for determining the feasibility to grow cotton in each county in the study area because producers



a. Long-term average annual heat units **b.** Long-term average potential cotton yield

Fig. 2. Spatial distribution of county-wide long-term average total heat units (THU) and potential cotton yield (PCY) in the study area.

of the Texas counties in the Central High Plains have shown that cotton can be grown economically with approximately 1000°C heat units (Howell et al., 2004). There were 14 counties in the study area (9 in Kansas) that recorded between 800 and 999°C heat units. The remaining 12 counties recorded heat units less than 800°C. Most of these counties were found in the Northern High Plains.

Potential Cotton Yield

County-wide annual average PCY showed a trend similar to long-term average THUs (Fig. 2b). The average PCY varied from 569 to 2518 kg ha^{-1} for counties with 1000°C or more heat units. Comparison of estimated average PCY values with measured data for Lubbock County, TX, and Pratt County, KS, indicated that estimated average PCY values were comparable to the measured range of cotton yield. The estimated long-term average PCY for Lubbock County was 1756 kg ha^{-1} compared with a measured cotton yield range of 839 to 1630 kg ha^{-1} over 12 yr (1988–1999) under full irrigation conditions (Wanjura et al., 2002). Crop performance tests conducted by the Kansas Research and Extension, Kansas State University (2007) over 3 yr (2001–2003) reported a cotton yield range of 459 to 1392 kg ha^{-1} for Pratt County under unknown irrigation conditions. The estimated long-term average PCY for Pratt County (1271 kg ha^{-1}) was well within the reported range.

Figures 3a, 3b, and 3c show the spatial distribution of county-wide PCY that can be expected every year ($P = 0.99$), 4 out of 5 yr ($P = 0.80$), and 3 out of 4 yr ($P = 0.75$) in the study area. Table 2 presents number of counties in each yield group based on a 30-yr average potential cotton yield and three different scenarios With the every year scenario, the county-wide annual PCY varied from zero to 1744 kg ha^{-1} with an average of 403 kg ha^{-1}. About 39% (51 counties) of all counties in the study area were estimated to have a PCY more than 500 kg ha^{-1} (Fig. 3a). The PCY varied between 500 and 1000 kg ha^{-1} for 33 counties and exceeded 1000 kg ha^{-1} for 18 counties (15 of those from Texas). Only 2 counties along the southern Kansas border exceeded 1000 kg ha^{-1}. In the 4 out of 5 yr scenario, the county-wide annual PCY varied from zero to 2031 kg ha^{-1} with an average of 709 kg ha^{-1} (Fig. 3b). Forty-four counties had estimated PCYs within the 500 to 1000 kg ha^{-1} and 40 counties exceeded 1000 kg ha^{-1} (8 of those from Kansas). A similar trend was found with the 3 out of 4 yr scenario, where the county-wide annual PCY varied from 0 to 2307 kg ha^{-1} (Fig. 3c). Ninety counties had estimated PCYs of 500 kg ha^{-1} with more than 57% of those exceeding 1000 kg ha^{-1}.

The higher the P value, the lower the yield risk and vice-versa. The PCYs for the study area increased as the P value decreased and were less than the long-term average PCY (1040 kg ha^{-1}), indicating that higher cotton yields are associated with higher risks. For example, in the study area, producers can expect to achieve an average PCY of at least 403 kg ha^{-1} every year ($P = 0.99$). However, they can also expect to achieve a PCY of at least 805 kg ha^{-1} per year in 3 out of 4 yr ($P = 0.75$). This is about two times the average PCY that can be achieved every year, indicating that producers may have a better chance to increase their profit with yield goals that can be attained in 3 out of 4 yr. However, a detailed assessment of agricultural input costs with different yield goals is needed for this evaluation and it is beyond the scope of this study. In the 3 out 4 yr scenario, 41 counties recorded PCYs more than 1000 kg ha^{-1} and

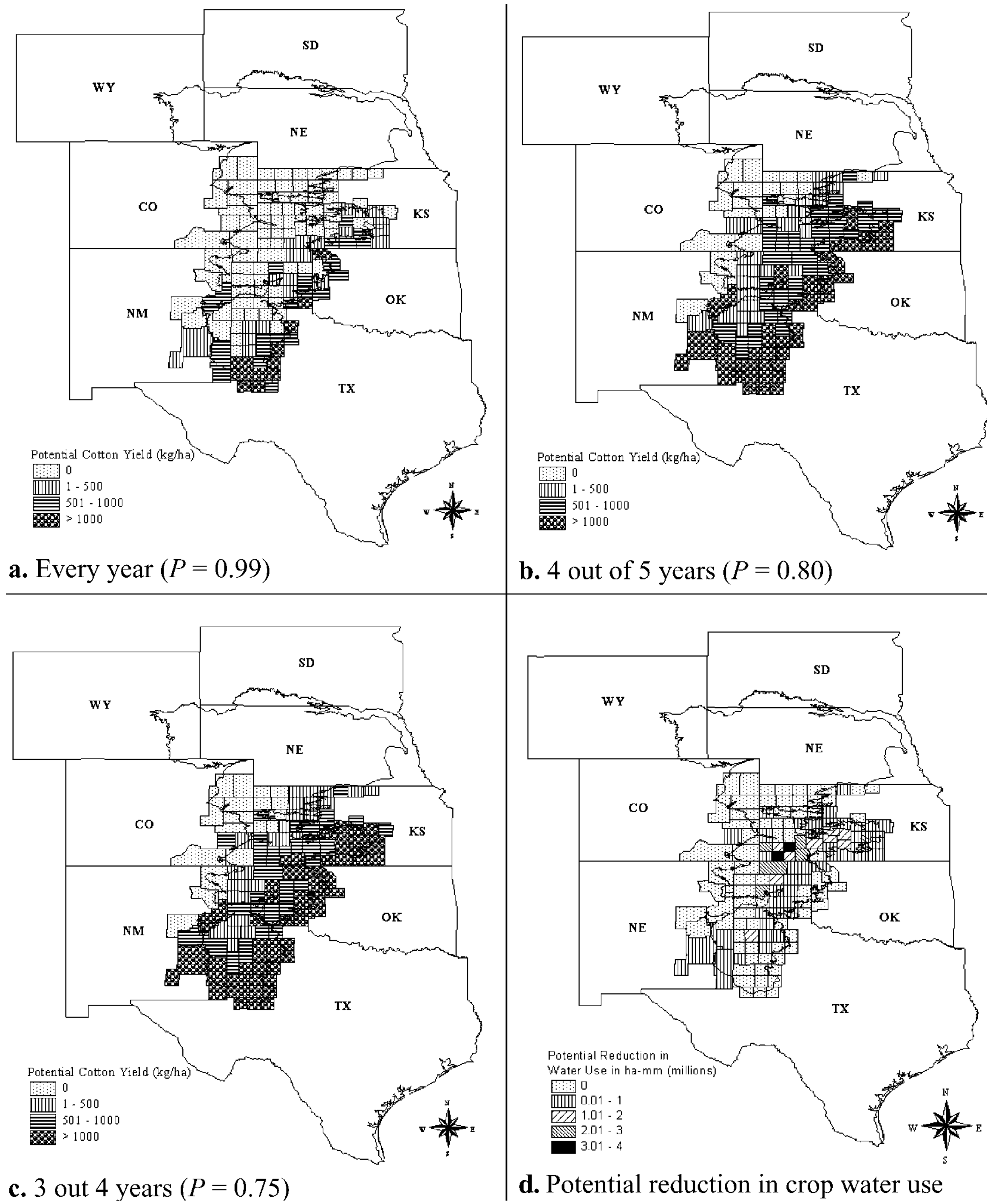


Fig. 3. Spatial distribution of county-wide potential cotton yield (PCY) in every year (P = 0.99), 4 out of 5 yr (P = 0.80), and 3 out of 4 yr (P = 0.75) and potential reduction in crop water use if 50% irrigated corn area was switched to cotton in the study area.

14 of those are located in south-central Kansas (Fig. 3c) where corn is still the major crop of choice under irrigated conditions. This may be partly due to the lower elevation from mean sea level of these counties.

Potential Reduction in Crop Water Use

Figure 3d illustrates the county-wide potential reduction in crop water use if producers were to convert 50% of their total irrigated corn area to cotton in counties that had a yield of at least 500 kg ha^{-1} lint in 3 out of 4 yr. This converts approximately 250,000 ha presently under irrigated corn (National Agriculture Statistics Service, 2005) to cotton and provides a potential annual reduction in withdrawal of ground water for irrigation purposes of about 465,000 mL (0.465 km^3). Approximately 73% of the reduction in water use occurs in Kansas counties because of the relatively large area of

Table 2. Number of counties in each yield group based on a 30-yr average potential cotton yield and three different scenarios.†

PCY	Number of counties			
	P = 0.99 (every year)	P = 0.8 (4 of 5 yr)	P = 0.75 (3 of 4 yr)	Based on 30-yr average PCY
kg ha^{-1}				
0	55	21	18	4
1–500	25	26	23	22
501–1000	33	44	39	41
>1000	18	40	51	64

† P, exceedance probability; PCY, potential cotton yield.

irrigated corn and small area of cotton. Lower potential reductions in crop water use in the Southern High Plains counties are due to the fact it is the part of the Texas cotton belt and most of the crop land is already under cotton.

CONCLUSIONS

The Ogallala Aquifer under the Central and the Southern High Plains is facing declining water levels. One of the options to optimize the use of limited irrigation water is to look for drought-tolerant and economically viable alternative crops. Producers in the Texas Panhandle have shown that economically viable cotton can be grown with about 1000°C heat units. In this study, we evaluated the feasibility of growing cotton in the Ogallala Aquifer Region based on PCY calculated from heat units. County-wide potential yield estimates over 30 yr (1971–2000) indicate that most counties in the Southern and Central High Plains provide suitable climatic conditions to grow cotton. Yield goals based on a 3 out of 4 yr return period may give better profits to producers than lint yield that can be expected every year. However, management uncertainties such as water use efficiency (Tronstad et al., 2003), fuel, fertilizer and pest management costs (Siebert et al., 2006), planting and harvesting schedule (Unruh and Silvertooth, 1997), ginning capacity (Clay et al., 2006), and available subsidies may require further consideration to estimate potential cotton yield and profitability. Nevertheless, these data show that cotton is a suitable alternative crop for the Central High Plains of the Ogallala Aquifer Region. Significant reduction in water withdrawals from Ogallala for irrigation is probable if producers were to convert 50% of their irrigated corn area to cotton.

REFERENCES

Baumhardt, R.L., and J. Salinas-Garcia. 2006. Dryland agriculture in Mexico and the U.S. Southern Great Plains. p. 341–364. *In* G.A. Peterson et al. (ed.) Dryland agriculture. 2nd ed. ASA, CSSA, and SSSA, Madison, WI.

Brown, E., S. Pregitzer, D. Reed, and J. Burton. 2000. Predicting daily mean soil temperature from daily mean air temperature in four northern hardwood forest stands. For. Sci. 46:297–301.

Clay, P.A., K.M. Young, and E.R. Taylor. 2006. Effect of heat unit accumulation on cotton defoliation, lint yield, and fiber quality. Arizona Cotton Rep. P-145:245–250.

Colaizzi, P.D., S.R. Evett, and T.A. Howell. 2004. Irrigation capacities and methods for cotton in the Northern High Plains. p. 154–162. *In* K.A. Rainwater and T.M. Zobeck (ed.) High Plains groundwater resources: Challenges and opportunities, Conference Proc. Texas Tech University Water Resources Center, Lubbock, TX.

Davidonis, G.H., A.S. Johnson, J.A. Landivar, and C.J. Fernandez. 2004. Cotton fiber quality is related to boll location and planting date. Agron. J. 96:42–47.

Davis, D.M., P.H. Gowda, D.J. Mulla, and G.W. Randall. 2000. Modeling nitrate-nitrogen leaching in response to nitrogen fertilizer rate and tile drain depth or spacing for southern Minnesota, USA. J. Environ. Qual. 29:1568–1581.

Gupta, S.C., W.E. Larson, and R.R. Allmaras. 1984. Predicting soil temperature and soil heat flux under different tillage-surface residue conditions. Soil Sci. Soc. Am. J. 48:223–232.

Howell, T.A., S.R. Evett, J.A. Tolk, and A.D. Schneider. 2004. Evapotranspiration of full-, deficit-irrigated and dryland cotton on the northern Texas High Plains. J. Irrig. Drain. Eng. 130:277–285.

Esparza, A.M., P.H. Gowda, R.L. Baumhardt, and C.A. Robinson. 2006. Thermal viability of cotton production in the Ogallala Aquifer Region. Proc. of the West Texas A&M Univ. 12th Annu. Student Res. Conf., 3 Mar. 3 2006.

ESRI. 2002. Arcview version 3.3. ESRI, Redland, CA.

Haan, C.T., B.J. Barfield, and J.C. Hayes. 1994. Design hydrology and sedimentology for small catchments. Academic Press, San Diego, CA.

Kang, S., S. Kim, S. Oh, and D. Lee. 2000. Predicting spatial and temporal patterns of soil temperature based on topography, surface cover and air temperature. For. Ecol. Manage. 136:173–184.

Kansas State University. 2007. Labette Co. dryland cotton performance test, 2003. Available at http://kscroptests.agron.ksu.edu/pdf/3cotton.pdf [verified 20 July 2007]. Kansas State Univ., Manhattan.

Liakatas, A., D. Roussopoulos, and W.J. Whittington. 1998. Controlled-temperature effects on cotton yield and fiber properties. J. Agric. Sci. 130:463–471.

McGuire, V.L., M.R. Johnson, R.L. Schieffer, J.S. Stanton, S.K. Sebree, and I.M. Verstraeten. 2003. Water in storage and approaches to ground-water management, High Plains aquifer, 2000. Circ. 1243. U.S. Department of the Interior, Washington, DC, and U.S. Geological Survey, Reston, VA.

McMahon, J., and A.J. Low. 1972. Growing degree days as a measure of temperature effects on cotton. Cotton Growing Rev. 45:91–100.

Munro, J.M. 1987. Cotton. 2nd ed. Longman Scientific & Technical, New York.

National Agriculture Statistics Service. 2005. Crops state and county data. NASS, Washington, DC.

National Climatic Data Center. 2002. Cooperative summary of the day TD3200 CD. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Asheville, NC.

New, L., and D. Dusek. 2005. Ogallala Aquifer 2004 annual report: Crop irrigation and production. Texas Cooperative Extension Service, Amarillo, TX.

Paul, K.I., P.J. Polglase, P.J. Smethurst, A.M. O'Connell, C.J. Carlyle, and P.K. Khanna. 2004. Soil temperature under forests: A simple model for predicting soil temperature under a range of forest types. Agric. For. Meteorol. 121:167–183.

Peng, S., D.R. Krieg, and S.K. Hicks. 1989. Cotton lint yield to accumulated heat units and soil water supply. Field Crops Res. 19: 253–262.

Reddy, K.R., G.H. Davidsons, A.S. Johnson, and B.T. Vinyard. 1999. Temperature regime and carbon dioxide enrichment alter cotton boll development and fiber properties. Agron. J. 91:851–858.

Reddy, K.R., H.F. Hodges, and V.R. Reddy. 1992a. Temperature effects on cotton fruit retention. Agron. J. 84:26–30.

Reddy, K.R., V.R. Reddy, and H.F. Hodges. 1992b. Temperature effects on early season cotton growth and development. Agron. J. 84:229–237.

Roussopoulos, D., A. Liakatas, and W.J. Whittington. 1998. Controlled-temperature effects on cotton growth and development. J. Agric. Sci. 130:451–462.

Sansone, C., T. Isakeit, R. Lemon, and B. Warrick. 2002. Texas cotton production: Emphasizing integrated pest management. Texas Cooperative Extension, Texas A&M University System, B-6116, 4–02.

Siebert, J.D., B.R. Leonard, and A.M. Stewart. 2006. Cotton (*Gossypium hirsutum* L.) yield and fiber-quality response to premature insect-simulated and harvest-aid defoliation. J. Cot. Sci. 10:9–16.

Steiner, J.J., and T.A. Jacobsen. 1992. Time of planting and diurnal soil temperature effects on cotton seedling field emergence and rate of development. Crop Sci. 32:238–244.

Tronstad, R., J.C. Silvertooth, and S. Husman. 2003. Irrigation termination of cotton: An economic analysis of yield, quality, and market factors. J. Cot. Sci. 7:86–94.

Unruh, B.L., and J.C. Silvertooth. 1997. Planting and irrigation termination timing effects on the yield of Upland and Pima cotton. J. Prod. Agric. 10:74–97.

Waddle, B.A. 1984. Crop growing practices. p. 234–264. *In* R.J. Kohel and C.F. Lewis (ed.) Cotton. ASA, CSSA, and SSSA, Madison, WI.

Wanjura, D.F., D.R. Upchurch, J.R. Mahan, and J.J. Burke. 2002. Cotton yield and applied water relationships under drip irrigation. Agric. Water Manage. 55:217–237.

Wheeler, E., J. Johnson, E. Segarra, and P. Johnson. 2004. The impacts of the Ogallala Aquifer characteristics on water use and conservation: The case of Hale County. p. 72–81. *In* K.A. Rainwater and T.M. Zobeck (ed.) Proc. High Plains groundwater resources: Challenges and opportunities. 7–9 Dec. 2004. Texas Tech Univ. Water Resources Center, Lubbock, TX.

Womach, J. 2004. Cotton production and support in the United States. CRS Report to Congress, Order Code RL32442, Resources, Science, and Industry Div., Congressional Research Service, The Library of Congress, Washington, DC.

Wrona, A.F., J.C. Banks, K. Hake, K. Lege, M. Peterson, B. Roberts, C.E. Snipes, and J. Supak. 1996. Achieving a clean finish. Cot. Physiol. Today 7:25–31.